Experimental proof of principle of the Neutrino Tagging technique at NA62

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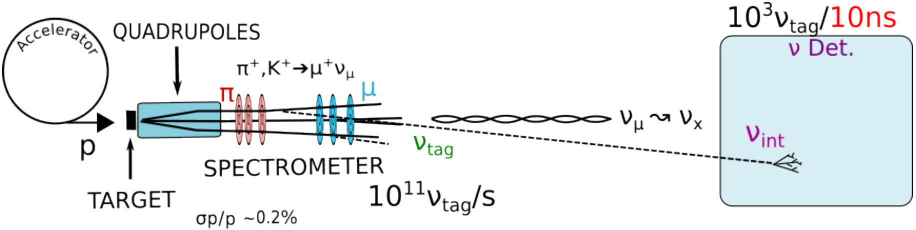
NuFact 2023

Outline

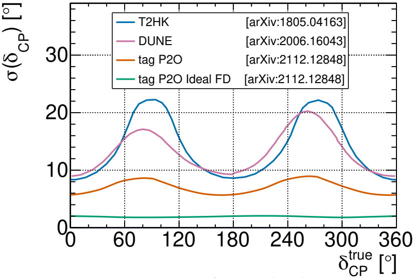
Neutrino Tagging

- Neutrino Tagging: method for accelerator based neutrino experiments
- Instrument a beam line with spectrometers
- Kinematically reconstruct each ν originating from a $\pi^+ \to \mu^+ \nu_\mu$ decay $\to$ *tagged* ν
- Associate *interacting* ν at Far Detector to its tagged ν
- Main advantages:
    - energy resolution < 1%, no energy scale
    - improved beam knowledge



Neutrino Tagging - Motivation

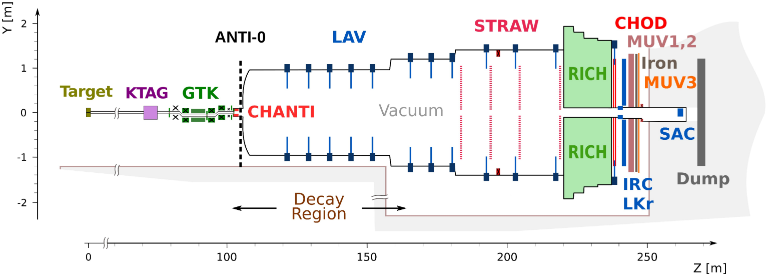
- At a tagged Short Base Line Experiment: (see L. Munteanu's talk)
  - precise flux knowledge → measure at 1% level ν_e x-sec and ν_μ differential x-sec
  - tagged ν energy determined independently of its interaction → refine interaction models
- These measurements would strongly improve the physics potential of upcoming LBLE:
- At a tagged Long Base Line Experiment:
  - setup with a natural water Cherenkov detector (like KM3NeT/ORCA) would allow to **measure δ_{CP} with unprecedented precision**.
- Both SBL and LBL are being studied, together with ENUBET, by the Physics Beyond Colliders (PCB) group @ CERN



M. Perrin-Terrin, Eur. Phys. J. C (2022) 82:465
S. Aiello et al, Eur. Phys. J. C 82, 26 (2022)

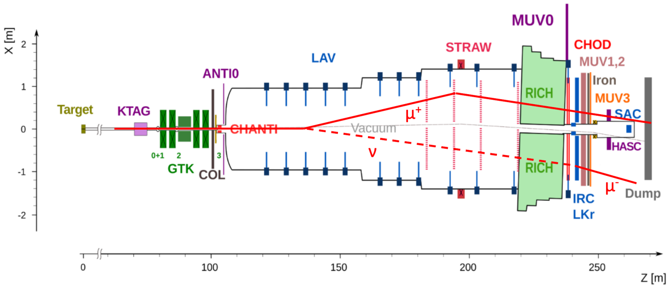
The NA62 experiment

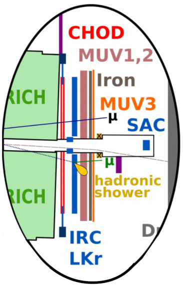
Feasibility study of tagging - NA62



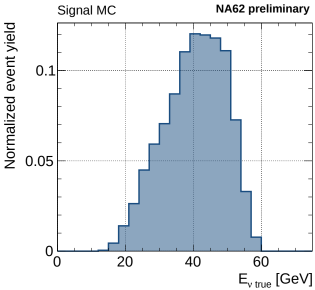
- NA62 is a fixed-target experiment in the North Area of the SPS at CERN
- NA62's main purpose is the measurement of the branching ratio of the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ rare decay (SM signal Br = $(8.4 \pm 1.0) \cdot 10^{-11}$)
- **Desirable features for ν tagging proof of principle**
- NA62's high intensity kaon beam at 75 GeV/c delivers a nominal rate of $\mathcal{O}(10^{12})K^+$ decays per year

Tagging at NA62



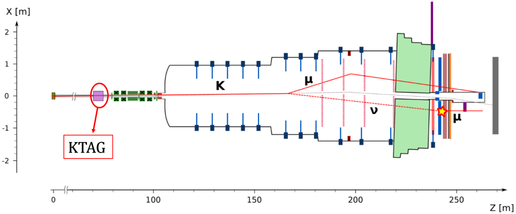


- Goal: search for $K^+ \rightarrow \mu^+ + \nu_\mu$ ($K\mu\nu$) with:
  - K^+ reconstructed by tracker
  - μ^+ reconstructed by tracker
  - ν interacting in the EM calorimeter (20ton LKr)
- ν interaction probability: $\mathcal{O}(10^{-11})$
- Interaction channel: CC-DIS: $\nu \rightarrow$ shower + μ^-
- Exploit μ^+, shower and μ^- for triggering strategy



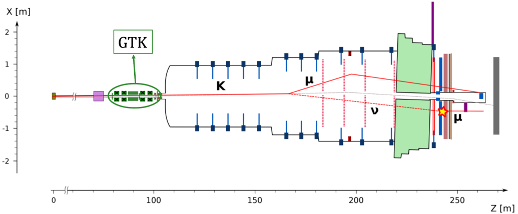
Main subdetectors involved

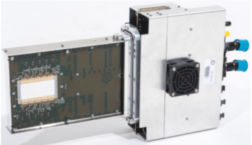
- KTAG: differential Cherenkov counter equipped with 8 arrays of photodetectors, identifies the K^+ in the beam
- Beam: 750MHz over 3s spills
- Composition: **6%** K^+, 70% π^+, 23% p

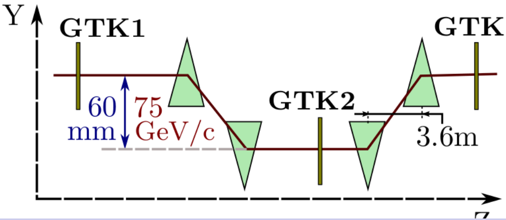


Main subdetectors involved

- GigaTracKer (GTK): silicon pixel spectrometer with 130 ps hit time resolution, reconstructs time and 4-momentum of incoming beam particles
- $\sigma_p/p = 0.2\%$, $\sigma_\theta = 16$ mrad

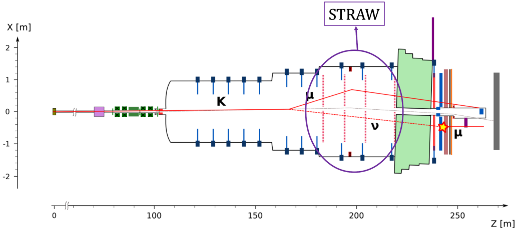






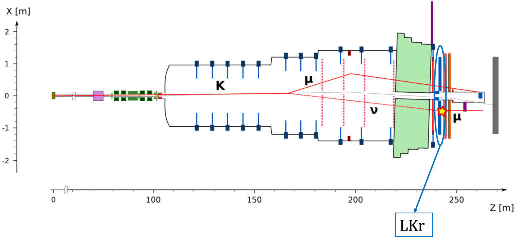
Main subdetectors involved

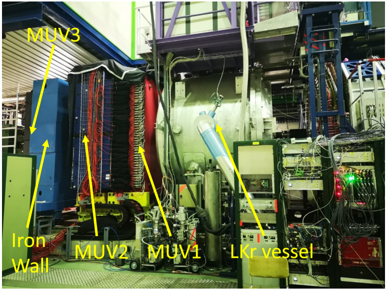
- STRAW: straw tube spectrometer that reconstructs the properties of charged particles produced in K decays



Main subdetectors involved

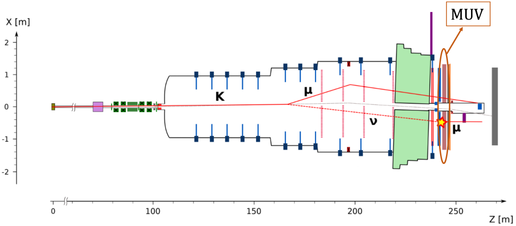
- LKr: electromagnetic calorimeter filled with about 9000 l of liquid Krypton at 120 K

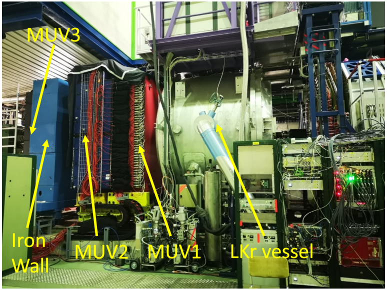




Main subdetectors involved

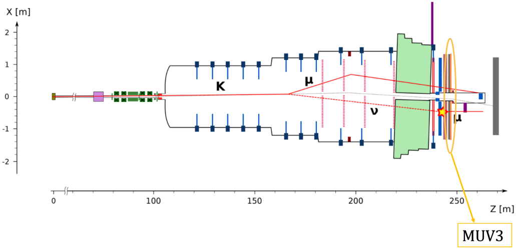
- MUV1 and 2: 66 ton hadron calorimeter

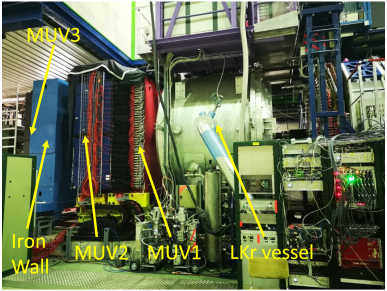




Main subdetectors involved

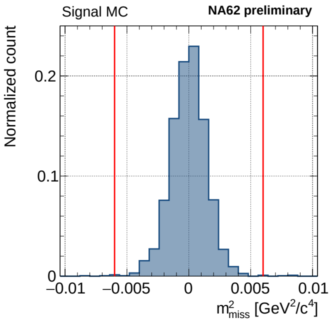
- MUV3: 50 mm thick scintillator tiles, placed behind LKr, MUV1 and 2, and an iron wall, used for muon ID

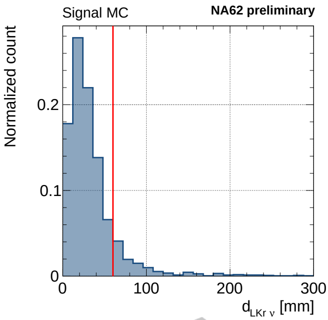




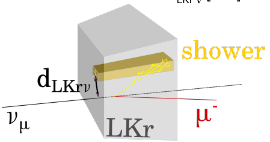
Analysis strategy

Analysis strategy





- Blind analysis strategy
- Signal region defined as:
  - $|m^2_{miss}| = |(P_{K^+} - P_{\mu^+})^2| < 0.006\,\text{GeV}^2/\text{c}^4$
  - $|d_{LKr}| < 60\,\text{mm}$



- Backgrounds assessed with data driven method on side bands; 2 background sources:
  - Overlaid $K\mu\nu$: $K \to \mu\nu$ with extra in-time activity → studied in side bands of d_{LKr}
  - Mis-reconstructed kaon decays → studied in side bands of m^2_{miss}.

Analysis strategy

- 2022 data sample has been analyzed
- Expected event rate:

$$N^{exp}_{\text{signal}} = N_{K^+} \cdot \mathcal{B}(K^+ \to \mu^+ \nu_\mu) \cdot P_{\text{int,LKr}} \cdot \epsilon_{\text{signal}}$$

- Use $K \to \mu\nu$ (no ν interaction) decays as normalization sample:

$$N_{K^+} = \frac{N_{\text{norm}}}{\epsilon_{\text{norm}} \cdot \mathcal{B}(K^+ \to \mu^+ \nu_\mu)}$$

$$N^{exp}_{\text{signal}} = N_{\text{norm}} \cdot \frac{\epsilon_{\text{signal}}}{\epsilon_{\text{norm}}} \cdot P_{\text{int,LKr}}$$

- Signal and normalization common efficiency terms cancel in the ratio
- Signal efficiency estimated thanks to a MC sample (GENIE) [a]

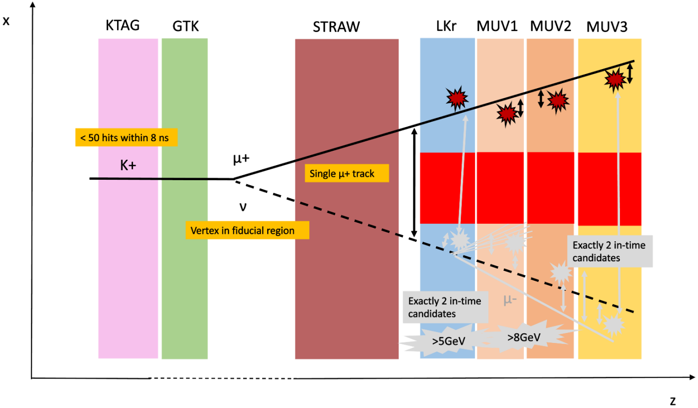
[a] Thanks to Marco Roda, Costas Andreopoulos for helping us implementing it in NA62 SW

Offline selection

- Need a **very** clean signal → strict selection
- Large background rejection factor

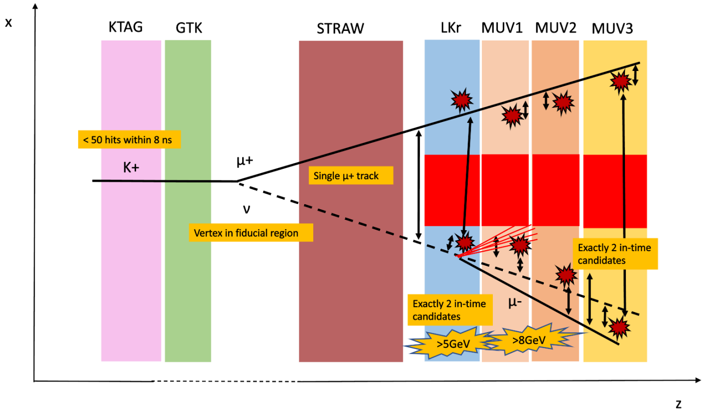
Common selection - signal and normalization

- Single positively charged track matched to LKr, MUV1, MUV2 and MUV3 candidates
- μ^+ PID
- photon rejection
- ν extrapolated position inside LKr acceptance

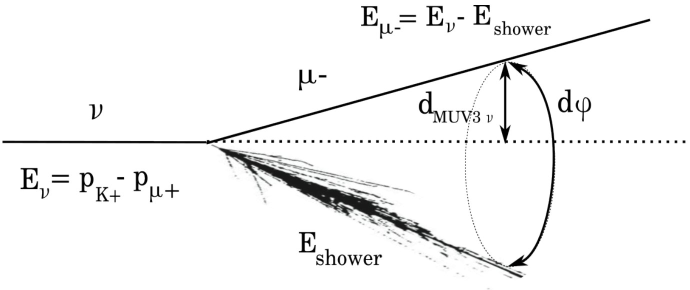


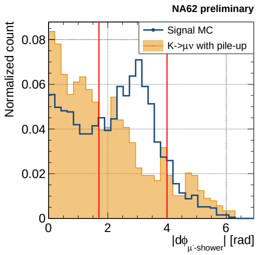
ν interaction offline selection

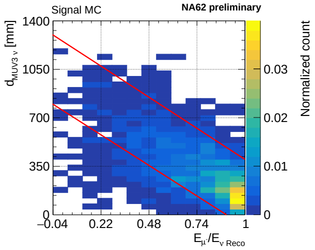
- Step 1: ν interaction associated to activity in LKr, MUV1, MUV2, MUV3 in time and space
- Step 2: Extra activity rejection
- Step 3: Energy requirements
- Step 4: Interaction topology

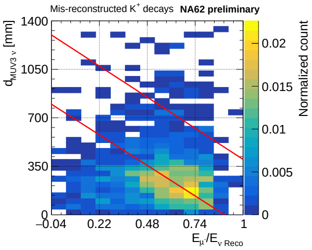


Interaction topology





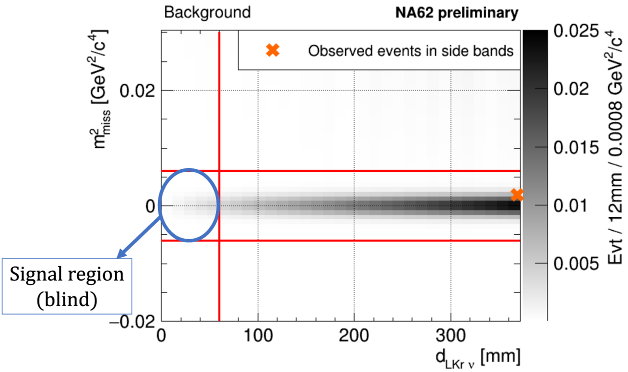




Signal and background yields

Background assessment

Background pollution estimated with data-driven method, in side bands of SR



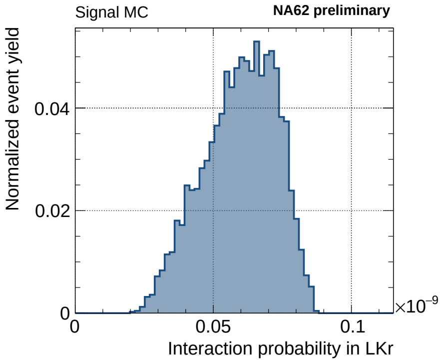
$$N^{exp}_{bkg}(\text{Mis}-\text{reco } K^+) = 0.0014 \pm 0.0007_{stat} \pm 0.0002_{syst}.$$

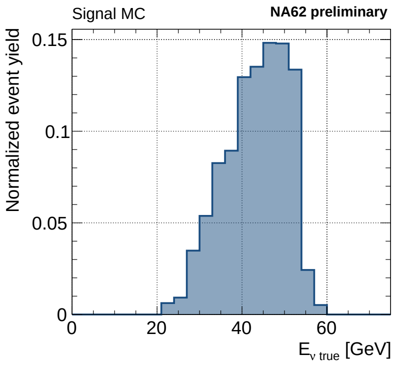
$$N^{exp}_{bkg}(\text{OV } K\mu\nu) = 0.04 \pm 0.02_{stat} \pm 0.01_{syst}.$$

Variables for signal yield computation

- $P_{int,LKr} = (6.0 \pm 0.1_{syst}) \cdot 10^{-11}$
- $N_{norm} = (1.49 \pm 0.02_{syst}) \cdot 10^{11}$ from $K\mu\nu$ event yield
- $\epsilon_{signal} = (2.55 \pm 0.15_{stat} \pm 0.04_{syst})\%$

$$\mathbf{N^{exp}_{signal} = 0.228 \pm 0.014_{stat} \pm 0.011_{syst}}$$





Summary

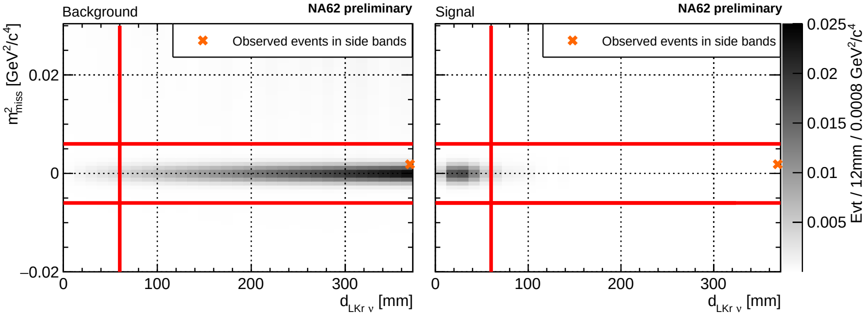
- In 2022 data sample:

$$N^{exp}_{\text{signal}} = 0.228 \pm 0.014_{stat} \pm 0.011_{syst},$$
$$N^{exp}_{bkg} = 0.0014 \pm 0.0007_{stat} \pm 0.0002_{syst},$$
$$N^{exp}_{bkg}(OV\ K\mu\nu) = 0.04 \pm 0.02_{stat} \pm 0.01_{syst}.$$

Probability for total event yield $\mathbf{N^{exp}_{events} = 0.2694}$

- for 0 data events p = 0.7638
- for 1 data event p = 0.2058
- for 2 data events p = 0.0277.

- Signal-to-noise: 5.5

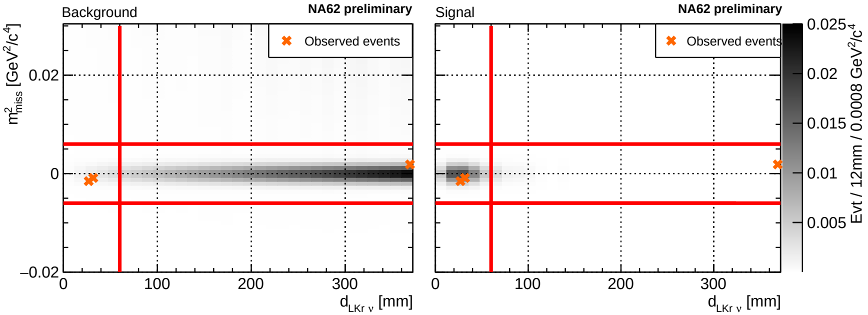


Revealing signal region content

- Results approved for unblinding by NA62 Collaboration
- Unblinding on July 27, 2023

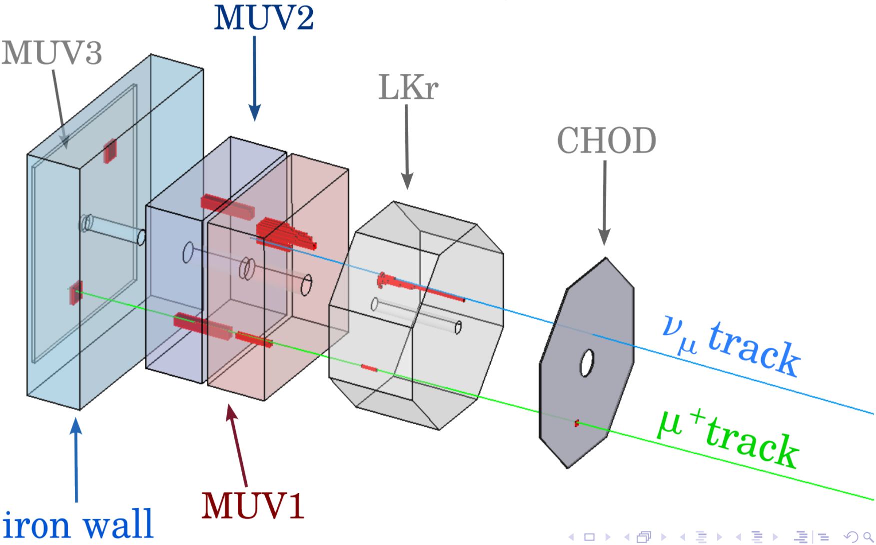
Opening the box in signal region

Two events are found in signal region!!



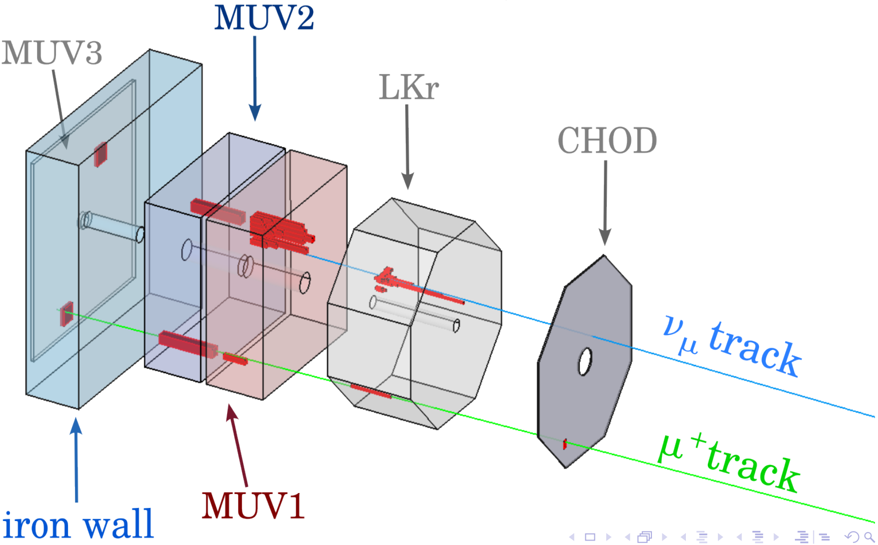
Event Display - Event A

- $p_{\mu^+} = 25.25$ GeV/c
- $E_\nu = 52.1$ GeV



Event Display - Event B

- $p_{\mu^+} = 18.74$ GeV/c
- $E_\nu = 57.5$ GeV



Conclusions

- NA62 experiment has been exploited as a miniature tagged experiment to demonstrate feasibility of the technique using $K^+ \rightarrow \mu^+ \nu_\mu$
- Blind analysis performed, expected $N_{signal}^{exp} = 0.228 \pm 0.014_{stat} \pm 0.011_{syst}$ signal events
- Signal-to-noise ratio 5.5
- 2 events found in signal region upon opening the box
- Crucial first step achieved toward the design of a full scale tagged experiment.

Backup

Signal yield

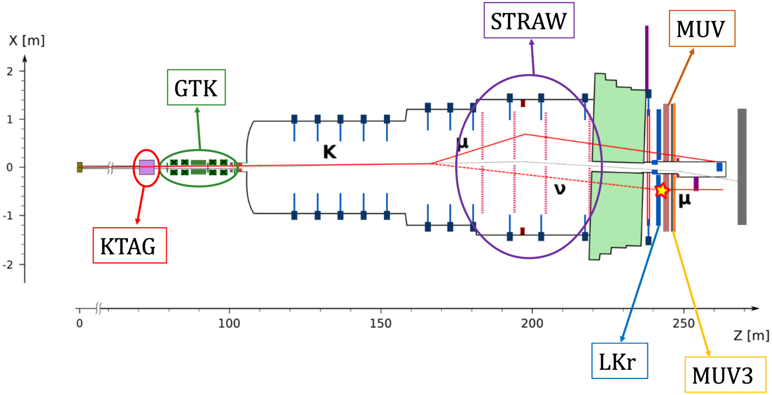
$N_{K\mu\nu} = N_{K\mu\nu}^{mask2-ext} \cdot D_{min-bias}^{mask2} = (1.49 \pm 0.02_{syst}) \cdot 10^{11}$ from normalization event yield

$$N_{K\mu\nu *}^{exp} = N_{K\mu\nu} \cdot A_{K\mu\nu *}^{int} \cdot \epsilon^{RV} \cdot \epsilon_{E5}^{sel} \cdot \epsilon_{MOQX}^{sel} \cdot \epsilon_{L1}^{sel} \cdot P_{int,LKr}$$
$$= \mathbf{0.228 \pm 0.014_{stat} \pm 0.011_{syst}} \quad (1)$$

Contribution	Value and uncertainty
$P_{int,LKr}$	$(6.0 \pm 0.1_{syst}) \cdot 10^{-11}$
$N_{K\mu\nu}$	$(1.49 \pm 0.02_{syst}) \cdot 10^{11}$
$A_{K\mu\nu *}^{int}$	$0.0421 \pm 0.0025_{stat} \pm 0.0015_{syst}$
ϵ^{RV}	$0.816 \pm 0.014_{syst}$
$\epsilon_{K\mu\nu *}^{MOQX}$	$0.976 \pm 0.007_{stat} \pm 0.001_{syst}$
$\epsilon_{K\mu\nu *}^{E5}$	$0.82 \pm 0.01_{stat} \pm 0.01_{syst}$
$\epsilon_{K\mu\nu *}^{L1/sel}$	$0.932 \pm 0.002_{stat}$

Trigger line

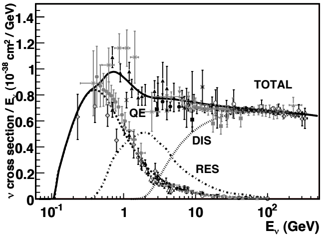
- Dedicated trigger line deployed in 2021, refined in 2022
- Trigger line selection: single downstream track before LKr with two muons at MUV3 with total energy deposit > 5GeV in LKr

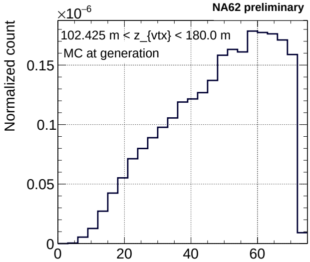


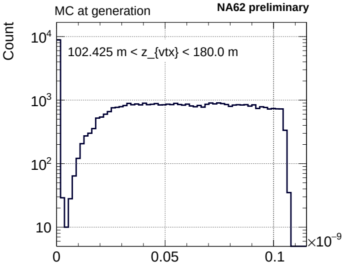
MC sample

- K^+ forced to decay in $\mu^+\nu_\mu$ at z = 102.425-180.0 m
- ν forced to interact in the LKr active volume
- ν interaction simulated with GENIE using CC-QE, RES, DIS
- Interaction final state and probability passed from GENIE to NA62MC
- Average interaction probability: $5 \cdot 10^{-11}$
- To account for final state modeling uncertainties, two extra samples are produced with the ν energy used to generate the final state biased by $\pm10\%$ to estimate systematic uncertainties

From Formaggio et al.

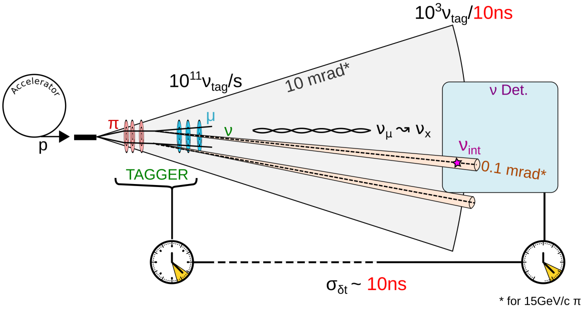






Neutrino Tagging - Implementation

- Implemented by instrumenting a beam line with beam spectrometers
- Upcoming tracker capabilities: $\mathcal{O}(10^{12})\pi/s$ [1], way below rate of standard LBL $\mathcal{O}(10^{18})\pi/s$
- Handles to limit particle flux:
  - slow extraction
  - narrow band (π momentum selection)
  - beam transverse size
- Unambiguous pairing between tagged and interacting ν



[1] A. Lai et al., First results of the TIMESPOT project on developments on fast sensors for future vertex detectors, 2020

Signal candidates properties

Variable	Event A	Event B
$d_{LKr\nu}$	31.9 mm	27.0 mm
m^2_{miss}	$-0.000\,88\,\mathrm{GeV}^2/\mathrm{c}^4$	$-0.0015\,\mathrm{GeV}^2/\mathrm{c}^4$
$d\phi_{LKr-MUV3}$	3.29 rad	3.24 rad
E_ν	52.1 GeV	57.5 GeV
p_{μ^+}	25.25 GeV/c	18.74 GeV/c
p_{K^+}	77.3 GeV/c	76.2107 GeV/c
$E_{LKr\ in\ time}$	13.36 GeV	7.67 GeV
$E_{MUV1\ in\ time}$	9.85 GeV	10.90 GeV
$E_{MUV2\ in\ time}$	2.48 GeV	2.80 GeV
E_{μ^-}/E_ν	0.68	0.78
n_{KTAG}	28	17
z_{vtx}	161.2 m	157.7 m
x, y at MUV3 μ^-	(550, 770) mm	(330, 770) mm
x, y at MUV3 μ^+	(-330, -770) mm	(-550, -990) mm

Table: Features of the two signal candidates found in the signal region.